

Alkali Line Profiles in Degenerate Dwarfs

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Abstract. Ultracool stellar atmospheres show absorption by alkali resonance lines severely broadened by collisions with neutral perturbers. In the coolest and densest atmospheres, such as those of T dwarfs, Na I and K I broadened by molecular hydrogen and helium can come to dominate the entire optical spectrum. Their profiles have been successfully modelled with accurate interaction potentials in the adiabatic theory, computing line profiles from the first few orders of a density expansion of the autocorrelation function. The line shapes in the emergent spectrum also depend on the distribution of absorbers as a function of depth, which can be modelled with improved accuracy by new models of dust condensation and settling.

The far red K I wings of the latest T dwarfs still show missing opacity in these models, a phenomenon similar to what has been found for the Na I line profiles observed in extremely cool, metal-rich white dwarfs. We show that the line profile in both cases is strongly determined by multiple-perturber interactions at short distances and can no longer be reproduced by a density expansion, but requires calculation of the full profile in a unified theory. Including such line profiles in stellar atmosphere codes will further improve models for the coolest and densest dwarfs as well as for the deeper atmosphere layers of substellar objects in general.

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INTRODUCTION

The alkali metals produce strong resonance absorption lines in all late-type dwarfs. Competing opacity sources such as the molecular bands of metal hydrides, titanium oxide or vanadium oxide, are removed from the atmosphere as one proceeds to cooler effective temperatures, and into the brown dwarf regime. First their opacity is replaced by continuous dust absorption characteristic of the spectra of L dwarfs, but as in late L and T dwarfs condensate grains settle below their fully radiative upper photosphere, the atmospheres become increasingly clear. The alkali elements bind less easily to molecules or grains, and thus their ground state transitions remain the last optical opacity sources, along with Rayleigh scattering by H₂ and He. Due to the extreme transparency of the atmosphere their line wings form under very high density conditions and thus show among the strongest pressure broadening effects observed in stellar atmospheres, due to collisions with H₂ and He. These massively broadened alkali lines therefore define the local pseudo-continuum out to several thousands of Ångströms from the line cores of the K I and Na I D doublets at 0.59 and 0.77 μm , as has been shown by Kirkpatrick et al. [1], Burrows et al. [2], Allard et al. [3]. The far wings of these lines show strong

departures from Van der Waals theory and a simple Lorentzian shape. Precise modelling of the line shapes requires detailed quantum-mechanical calculations, using accurate inter-atomic potentials as demonstrated by Allard et al. [4], Burrows and Volobuyev [5], Allard et al. [6].

BROWN DWARF MODEL SPECTRA

Detailed line profiles for all alkali resonance doublets (Li, Na, K, Rb, Cs) have been calculated by Allard et al. [6, 7], Allard and Spiegelman [8], Allard et al. [9, 10] for perturbation by both H_2 and He. These calculations, recently updated from the molecular potentials of Rossi and Pascale [11] for the H_2 interaction to the newer ones of Spiegelman [in preparation, see also 10], are included in our stellar atmosphere models calculated with the PHOENIX code [12]. Compared to the previous generation of brown dwarf spectra described by Allard et al. [3], the detailed profiles in particular of the NaI and KI doublets have produced much improved synthetic spectra of the red optical and near infrared region.

Alkali chemistry and condensation

Since the core, near and far wings of these strong lines form along an extended optical path through the atmosphere, one also needs to know the numbers of absorbing atoms at all depth points contributing to the line. These can vary considerably with depth, as alkali metals and other refractory elements are being depleted in brown dwarf atmospheres by condensation onto grains, and eventually sedimentation of the condensates into deeper layers [13]. Condensation of dust particles has to be considered for effective temperatures below 2500 K, i. e. essentially for all dwarfs later than spectral type M. At $T_{\text{eff}} < 2000$ K the top of the cloud deck starts to sink into deeper parts of the atmosphere, receding to the optically thick layers at T_{eff} of 1200 ... 1400 K, which marks the transition from spectral class L to T. Condensate fractions for such objects therefore can no longer be determined from chemical equilibrium calculations such as those used in the equation of state of Allard et al. [3]. In the ‘Dusty’ limit described in the former work condensates would be assumed to be present everywhere where they are thermodynamically stable, and to be in condensation/evaporation equilibrium with the gas phase. In contrast, in our current **Settl** models the amount of dust and the fraction of metals still present in the gas phase is calculated by comparing timescales for grain growth and turbulent mixing driven by convective overshoot. This approach has produced a much more realistic cloud model and an improved description of the L/T transition [14].

The Settl models, combining the new line profile calculations with the depth-dependent number densities of refractory elements, also show very good agreement with the observed line shapes of alkali metals (see Fig. 1). Even for the L/T transition objects, which are notoriously difficult to model, the optical spectrum is reproduced extremely well, allowing us to identify for the first time the satellite feature located in the blue wing of the potassium line [17]. But due to the complex cloud physics and

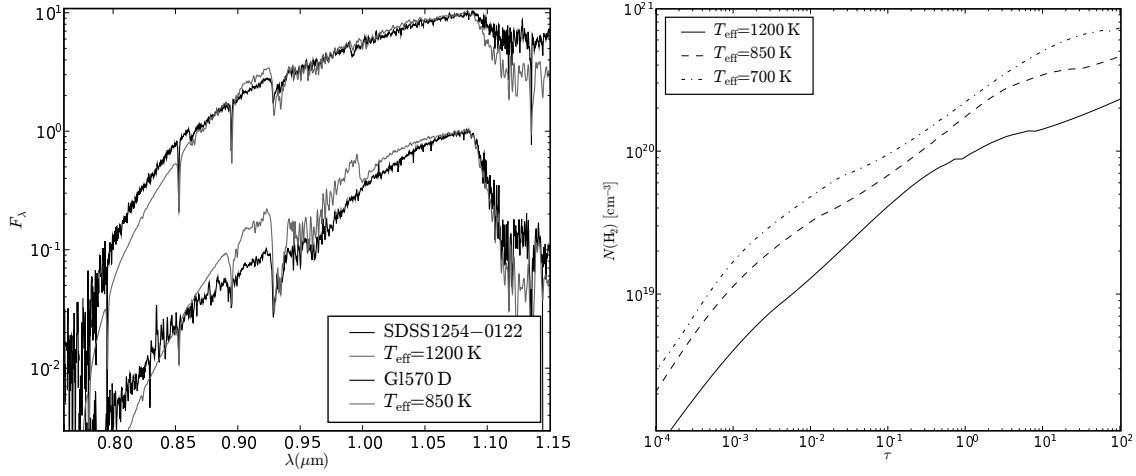


FIGURE 1. Left: Red wing of the KI doublet, in the spectra of the T2 dwarf SDSS1254–0122 and the T8 dwarf Gliese 570 D (black) [15, 16], compared to PHOENIX models calculated for $\log g$ of 5.25 (gray). All spectra have been normalised to the peak of the Y -band flux peak at $1.08 \mu\text{m}$, and the T2 observation and model are shifted upward by a factor of 10. Right: Number densities of molecular hydrogen as a function of optical depth for the atmosphere models shown on the left, and for a model for a very late T dwarf.

chemistry results of the settling model naturally depend sensitively on input parameters and correct implementation. This is illustrated in Fig. 2, where the effect of omitting just one of the species involved in the alkali metal chemistry is shown. Removing one potential sink for sodium not merely affects the fraction of sodium present in the gas phase, but also those of the other alkali metals which are coupled to it by a chemical reaction network, and produces strongly overestimated potassium absorption. Such effects are most visible in the cores and near wings of the alkali resonance lines, which form in the higher and cooler layers that are most affected by the depletion processes. In these regions the models still tend to predict too high concentrations of K I and therefore too much absorption out to several 100 \AA from the line core, indicating that we are still missing some aspects of the cloud chemistry.

Limitations of the line profiles

Comparison with the spectra of the coolest T dwarfs, such as Gl570D or 2MASS J0415–0935 shown in Figs. 1&2, however also reveals discrepancies in the very farthest parts of the KI line wings, which extend to the red nearly 3000 \AA into the Y -band flux peak. While this region is still reproduced well in early and mid-T dwarfs [see also 17], the models significantly underestimate the absorption in the far wing for late T dwarfs. As this part of the spectrum forms very deep in the atmosphere, where temperatures even in such cool brown dwarfs are too high for any alkali condensation to occur, shortcomings of the cloud model cannot be responsible for the mismatch in this case.

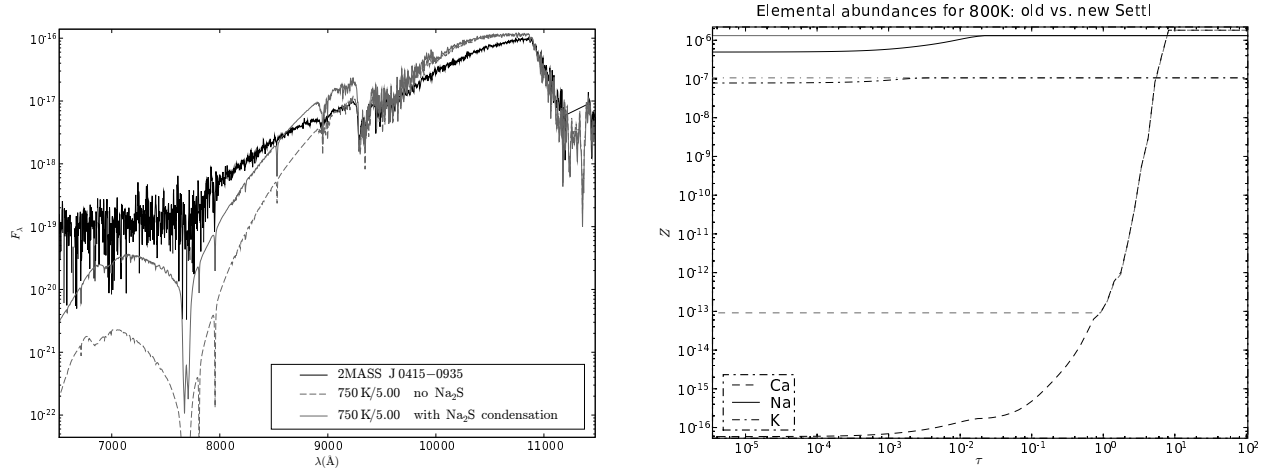


FIGURE 2. Left: Spectrum of the T8 dwarf 2MASS J0415–0935 [15, 16] with PHOENIX Settl model including complete formation and sedimentation of grains (solid), and comparison with one alkali-bearing condensate left out of the equation of state (dashed). The latter not only inhibits condensation of sodium, but also leaves much higher concentrations of gaseous potassium in the atmosphere. Right: Abundances of important alkaline (earth) metals for partial (gray) and full (black) implementation of depletion effects.

A possible explanation may be found by testing the applicability of our line formation code to the conditions of the coolest T dwarfs. We use profiles of the alkali metal resonance lines calculated for perturbations due to neutral He and H₂ as the Fourier transform of the autocorrelation function of the dipole moment within the adiabatic theory, as detailed in Allard et al. [6, 7]. In the PHOENIX implementation the depth-dependent line opacity is calculated by splitting the profile into a core component, which is describing the interactions at long distance in the impact approximation, leading to a Lorentzian line shape, and the far wings for close interactions that can produce the detunings of several 1000 Å observed in T dwarf spectra (see also the contribution of G. Peach, these proceedings). The latter is computed in the low density limit using an expansion of the autocorrelation function in powers of density, which for the present models has been developed to the third order and evaluated at a perturber density of 10¹⁹ cm^{−3}. While this method allows an easy (linear) scaling to different perturber densities, one has to be aware that only the core part explicitly includes multiple perturber effects, while the non-linear behaviour of the higher-order terms of the density expansion is not correctly taken into account. In addition, Allard et al. [7] have shown that at higher densities, where multiple perturber interactions become important even at close distances, higher perturber density does not merely increase the line strength, but affects the shape of the wings as well, and therefore the low density limit is only strictly applicable at densities up to 10¹⁹ cm^{−3} in the case of Na or K broadened by H₂ or He, and will quickly break down above 10²⁰ cm^{−3}. The density profiles in Fig. 1 show that this limit is quickly exceeded in T dwarfs at an optical depth of the order unity, where the far red wing of the K I doublet forms. While the H₂ density stays just below 10²⁰ cm^{−3} in mid-T dwarfs, it reaches several times that value for the latest T types in the case of massive brown dwarfs. For atmospheres of less than the log *g* = 5.25 shown here, densities would be

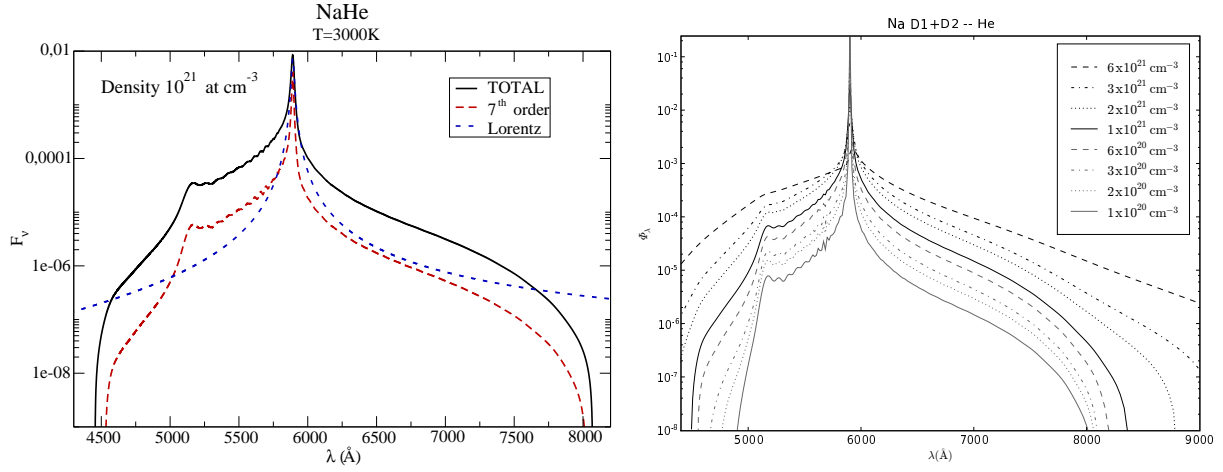


FIGURE 3. Left: Full unified profile of Na I D2 perturbed by 10^{21} cm^{-3} of He at 3000 K, compared to the 7th order expansion and Lorentzian [from 19]. Right: Full unified profiles of the Na I D2 line for He perturber densities from 1 to $60 \times 10^{20} \text{ cm}^{-3}$, all calculations at $T = 3000 \text{ K}$.

correspondingly lower, but such low gravities can only be expected for rather young objects [18]. We thus find evidence that the K I absorption in the *Y*-band is underestimated for the latest T dwarfs because their atmospheres significantly exceed the density range where the present line profile calculations may be applied. Line shapes calculated with the unified theory of Allard et al. [4] such as those described by Allard et al. [7] should improve that situation.

ALKALI LINES IN COOL WHITE DWARFS

Homeier et al. [19] have investigated possible broadening effects of the Na I D doublet at even higher perturber densities, occurring for metal-rich white dwarfs with a helium-dominated atmosphere. They found that the density of He as a perturber in two very cool white dwarfs showing very strong Na absorption could reach several 10^{21} to 10^{22} cm^{-3} , depending on exact composition and temperature. They have directly compared the results of the density expansion model and the unified theory for the Na I D lines under these conditions. The left side of Fig. 3 shows that at a He density of 10^{21} cm^{-3} even carrying the density expansion to the 7th order rather than just to the 3rd, the line strength in the wings falls short of the unified profile by almost an order of magnitude. Yet the impact approximation can only reproduce the profile within a few 100 Å from the line core [see also 9]. The right hand side illustrates that at the highest densities the far wings do not simply scale in strength, but also change their shape towards a wider profile, especially above 10^{21} cm^{-3} .

We expect a similar behaviour for the line shapes of the K I doublet with both He and H_2 as perturbers. While conditions in brown dwarfs are somewhat less extreme than in ultracool white dwarfs, this example shows that the coolest T dwarfs, too, require line profile calculations taking multiple collision effects into account in a unified theory.

DISCUSSION

New line profiles have greatly improved spectral models of all the alkali resonance lines. Remaining discrepancies with observed line shapes of brown dwarfs for the cores and near wings can be traced to shortcomings of the cloud model for the high atmosphere. A lack of absorption in the very far wings becomes evident in the latest T dwarfs. Comparison with Na I lines observed in cool white dwarfs support our interpretation that these discrepancies are due to the extreme perturber densities, and that unified line profiles are needed to model atmospheres at such high pressure. This will become more important with cooler brown dwarfs still being discovered, and spectral models for the yet to be found Y dwarfs needed. The additional opacity from alkali lines at high densities could also influence the radiative transfer in substellar atmosphere models even below the visible photosphere, possibly affecting the thermal structure, and thus cooling rate and evolution of both brown dwarfs and giant gas planets. Metal-rich cool white dwarfs may provide an important testbed for these new models.

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